TIMING AND KINEMATICS OF NEOGENE UPLIFT OF THE ABUKUMA
MASSIF, NORTHEASTERN HONSHU, JAPAN

A Thesis in
Geosciences
by
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Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

May 2009
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ABSTRACT

New structural and chronologic data from the inner forearc of the northeastern Japan convergent margin provide evidence for Pliocene to Quaternary thick-skinned deformation accommodated by a high-angle, near-coastal, margin-parallel reverse fault. This structure, the Futaba fault, bounds the exhumed Abukuma massif on the east and places Cretaceous granites in fault contact with Miocene to Pliocene near-shore to terrestrial, tephra-rich sands and silts. Recent uplift of the massif by slip along the Futaba fault is implied by a regionally extensive footwall syncline, the absence of Neogene sediments in the hanging wall, and high relief on the eastern margin of the massif. New structural field data and existing map data that characterize the surface expression of the fold are used as inputs in a kinematic fault related-fold model to constrain subsurface fault geometry and total slip for the Futaba fault. Results of forward trishear models show that the structure is best modeled as the result of deformation associated with ~2.2 km of slip along a 50º-75º west-dipping reverse fault. Dated tephra beds that span the transition from pre-growth to growth units at the southern tip of the fault bracket the onset of deformation between 3.95 - 5.6 Ma, and result in average slip rate of 0.4-0.6 mm/yr, an uplift rate of 0.4-0.5 mm/yr, and a shortening rate of 0.1-0.2 mm/yr. Inner forearc shortening along the Futaba fault is contemporaneous with offshore subsidence along the northeastern Japan margin, which has been interpreted to reflect basal erosion of the upper plate. The shortening along the Futaba fault and other contractional structures across the upper plate suggests that the entire forearc may be responding to changes in plate boundary tractions and that inner forearc shortening and outer forearc subsidence may be genetically linked. Inner forearc shortening may result in changes in forearc slope, loading of the outer forearc, and an increase in sediment supply to offshore basins. This suggests that a portion of the subsidence record previously interpreted to reflect basal erosion may be the result of shortening in the inner forearc, and that inner forearc shortening is an important contributor to mass balance of the subduction zone.
# TABLE OF CONTENTS

LIST OF FIGURES .................................................................................................................. v

LIST OF TABLES .................................................................................................................... vii

ACKNOWLEDGEMENTS ......................................................................................................... viii

1 Introduction ......................................................................................................................... 1

2 Geologic Background ......................................................................................................... 5

   2.1 Tectonic Setting ........................................................................................................... 5
   2.2 Stratigraphy ................................................................................................................ 7
   2.3 The Futaba Fault ......................................................................................................... 9

3 Field Observations and Motivation for Study ................................................................ 13

4 Methods .............................................................................................................................. 21

   4.1 The Trishear Kinematic Model ................................................................................... 21
   4.2 Simulation of Deformation .......................................................................................... 23
   4.3 Model Setup and Selection of Parameter Space ......................................................... 24
   4.4 Determination of a Best-fit Model ............................................................................. 27
   4.5 Stratigraphic Ages and Deformation Rates ............................................................... 28

5 Trishear Model Results ...................................................................................................... 32

   5.1 Hanging Wall Anticline ............................................................................................. 32
   5.2 Footwall Syncline ....................................................................................................... 34
   5.3 Deformation Rates .................................................................................................... 35

6 Discussion ............................................................................................................................ 45

   6.1 Geometry and Kinematics of the Futaba Fault ......................................................... 45
   6.2 Tectonic Interpretations .............................................................................................. 46

7 Conclusions ......................................................................................................................... 50

References ................................................................................................................................ 51

Appendix: MATLAB codes .................................................................................................... 56
LIST OF FIGURES

Figure 1–1 Digital elevation model and bathymetry of Japan showing tectonic boundaries. The Abukuma Massif is as basement-cored uplift located inboard of the Japan Trench. The trench marks the eastern boundary between the Okhutsk plate, where the Pacific plate subducts nearly orthogonal to the margin at a rate of 82 mm/yr. Elevation data obtained from SRTM3 data set; bathymetry data obtained from ETOPO2 data set. 4

Figure 2–1 Simplified geologic map of the Abukuma Massif (after Kubo et al., 2003), bound on the east by the Futaba fault. The Futaba fault is divided into the a) Namie segment b) Haramachi segment and c) Watari segment. The massif is cored by Cretaceous granites and older sedimentary and metasedimentary units. Along the Eastern flank of the Abukuma massif, stream cuts expose deformed Paleogene and Neogene strata along the footwall of the Futaba fault. Boxes denote locations of inset geologic maps along modeled profiles in Figure 3-1. 11

Figure 2–2 Stratigraphic column for the eastern flank of the Abukuma Massif (after Kubo et al., 2002). 12

Figure 3–1 Detail geologic maps at locations of modeled transects across the hanging wall anticline (A.) and the footwall syncline (B.). See figure 2-1 for locations. 17

Figure 3–2 Miocene pre-growth units of the Yunagaya Group are unconformably overlain by Pliocene growth strata of the Dainenji Formation of the Sendai Group at the southern tip of the Futaba fault. See Figure 2-1 for location. 18

Figure 3–3 Overturned Miocene beds of the Yunagaya Group are in fault contact with shallowly east-dipping Pliocene beds of the Dainenji Formation along a splay of the Futaba fault. See Figure 2-1 for location. 18

Figure 3–4 Panoramic view of the Abukuma Mountain front at the southern tip of the Futaba fault. Note the increase in hanging wall elevations and relief where the Futaba fault becomes emergent. See Figure 2-1 for location. 19

Figure 3–5 Reidel shears exposed in a quarry in the Futaba fault zone consistent with top to the east shear within a west dipping fault zone. See Figure 2-1 for location. 20

Figure 3–6 Footwall syncline developed in the Dainenji Formation along the Namie segment of the Futaba fault. See Figure 2-1 for location. 20

Figure 4–1 Setup for the velocity field solution to the trishear kinematic model for fault-related folds (after Zhender and Allmendinger, 2000). Deformation results from distributed simple shear within a triangular zone of width $\phi_1+\phi_2=\phi$, that is bound by $y=x\tan\phi$ and $y=-x\tan\phi$ and is fixed to a propagating fault tip $(\text{tip}_x, \text{tip}_y)$. The velocity field is solved for an x,y, coordinate system parallel to the fault ramp angle $\alpha$ and fixed to the fault tip. The velocity field propagates with the fault tip at a rate of $P/S(v,t)$ along the fault ramp, within an $X',Y'$coordinate space. Red arrows denote velocity field at time $t$. 29

Figure 4–2 Schematic of the observed data and determination of best-fit trishear models, as described in the text. A) Observed bed dip data $(x_i, y_i, \theta)$ gathered from folded sedimentary rocks along a surface profile. B) Quality of fit for a set of model parameter values is based on the RMS fit between observed bed dips and model bed slopes. Fault ramp angle ($\alpha$) and total slip (S) are estimated from the range of best fit parameter values at time $t$. 30

Figure 5–1 Most likely distributions of fault ramp angle and total slip for models of the hanging wall anticline along section A-A’. Histogram represent the frequency at which the selected parameter values result in a model fold that can reproduce observed bedding data with an RMS <5º. Superimposed curves
represent Gaussian distributions for the mean and standard deviation for fault ramp and total slip given RMS cutoff values of 5º, 4º, and 3º.

**Figure 5–2 A.** Best-fit trishear model for the hanging wall anticline along section A-A’. Top: Bedding dips in the exposed Miocene pre-growth strata (blue dip tabs) are used to constrain the most likely fault ramp angle, total slip, fault propagation to slip ratio (P/S), trishear angle (phi) and initial fault tip position for the Futaba fault. Bottom: Residuals between model bed dips and observed bed dips used to calculate RMS misfit for the best-fit model. Continued on following page.

**Figure 5–3** Range of initial and final fault tip positions that can reproduce bedding data for the hanging wall anticline along section A-A’ with an RMS<5º. Fault tip positions are contoured to show the minimum RMS value for a given fault tip coordinate. Solid line represents the most likely fault ramp angle, and dashed lines bound the range of fault ramps that can produce a model with RMS<5º.

**Figure 5–4** Range of propagation to slip ratios (P/S) and trishear angles (phi) that produce a fold that replicates observed bedding data with an RMS <5º for the hanging wall anticline along section A-A’. P/S and phi are contoured to the minimum RMS value for a given parameter pair.

**Figure 5–5** Cross sections across the hanging wall anticline along section A-A’ and the footwall syncline along section B-B’, based on results of trishear modeling. See Figures 2-1 and 3-1 for locations.

**Figure 5–6** Most likely distributions of fault ramp angle and total slip for models of the footwall syncline along section B-B’. The histogram and superimposed Gaussian distribution for the mean and standard deviation of the population show the frequency at which the ramp angle results in a model fold that can reproduce observed bedding data with an RMS <10º.
LIST OF TABLES

*Table 4-1* Input parameter distributions used for Monte Carlo simulations of fold geometry along sections A-A' and B-B'. __________________________________________________________ 31

*Table 5-1* Mean and standard deviation for best-fit trishear model parameters obtained from Monte Carlo simulations of the hanging wall anticline at section A-A' and of the footwall syncline at section B-B' (see Figures 2-1 & 3-1 for location) ____________________________________________ 43

*Table 5-2* Average slip rates, uplift rates, and shortening rates for the Futaba fault based on model-constrained ramp angle and total slip, and dated horizons bracketing the transition from pre-growth to growth strata in the hanging wall anticline. _____________________________________________ 44
ACKNOWLEDGEMENTS

I would like to thank my advisor Don Fisher and committee members Eric Kirby and Kevin Furlong, without whom this thesis would not exist, Gaku Kimura-san and Hiroki Watanabe-san for invaluable assistance and hospitality while in Japan, Kristin Morell for countless hours of help and support both in and out of the field, all the members of the extended Tectonics Lab, without whom I would not survive, my father, for always believing in me, encouraging me, and allowing me to pursue my dreams, my sisters Michele and Lisa, for going before me and helping me realize that there is a light at the end of the tunnel, my brother Mark, for always unexpectedly cheering me up at the right times, and finally, my mother, whom I love and miss dearly and with whom I hope someday to be able to share the stories of my travels. Funding for this project has been provided by the NSF EAR-Tectonics Division, GSA Graduate Research Grants, the P.D. Krynine Memorial Fund, and the Conoco Phillips Graduate Award.
1 Introduction

The northeast Japan convergent margin (Figure 1-1) is a non-accretionary subduction zone with a well-documented record of offshore Neogene subsidence and active shortening across the arc. The offshore subsidence record has been used to argue for basal tectonic erosion of upper plate material by thinning of outer forearc crust outboard of a rigid backstop (e.g. Clift & Vannucchi 2004, Scholl 1980, Scholl 1991, von Huene & Lallemand 1990). Late Neogene uplift and shortening of the arc and backarc of northeastern Honshu, Japan, however, has been documented across a network of faults and fault-related folds that extend from the Sea of Japan into the westernmost forearc (e.g. Sato 2002 van der Werff, 2000). This implies that the arc and inner forearc act as a deformable, rather than a rigid backstop.

The cause of the initiation of contraction across the Northeastern Japan arc is not well understood and the time of initiation of thrusting is constrained for only a few structures (e.g. Sato 1994, 1991). The transition of the arc from an extensional regime associated with the opening of the Sea of Japan to the modern day compressional stress regime is constrained to 15-3.5 Ma (Sato 1994). The initiation of reverse motion on two faults is bracketed to 4.3-2.4 Ma in the backarc along the Japan Sea coast and 0.9-0.5 Ma just east of the arc (Awata 1988, Sato 1994). Several contractional structures in the arc have been identified as high-angle, basement-involved faults interpreted to reflect positive basin inversion of pre-existing Miocene extensional grabens (Kato et al. 2006, Sato 2002), implying that modern day shortening may occur along reactivated Miocene extensional faults.

This system of reverse faults is currently mapped from the Sea of Japan to the western flanks of two basement-cored forearc highs, the Abukuma and Kitakami Massifs (Figure 1-1; AIST 2008). However, new field data and kinematic fault related fold modeling presented here suggest that this deformational front extends into the inner forearc at least to the eastern flank of
the Abukuma Massif, where the ~150 km long Futaba fault places Cretaceous, crystalline basement rocks in fault contact with deformed Neogene sedimentary cover sequence. This fault is not currently recognized as an active contractional structure (ie. AIST 2008, Ikeda et al. 2002) and Neogene-averaged slip rates, fault kinematics, and time of initiation of slip, have not been determined.

The Futaba fault is currently interpreted as a vertical to near-vertical fault with a slip sense that varies from left-lateral along the central segment of the fault, to reverse slip along the northern and southern segments (AIST 2008, Kubo et al. 2003). Holocene ruptures have been identified along the central 20 km of the fault, but the system is not catalogued among an inventory of active thrust faults in Japan (Ikeda et al. 2002). This interpretation of fault geometry and kinematics implies little to no Plio-Quaternary crustal shortening. Field observations, however, suggest Plio-Quaternary uplift of the Abukuma Massif by slip along an active, west-dipping, basement-involved, reverse fault. These observations include the identification of a regionally extensive, east-vergent fault-related fold, growth strata in the Pliocene section at the southern tip of the Futaba fault, and a steep mountain front into which hanging wall channels are deeply incised. This alternative fault geometry can produce significant crustal shortening and the mountain front morphology suggests that slip has continued into the Quaternary.

New structural field data and existing map data that characterize the surface expression of the fold are used as inputs into a kinematic fault related-fold model to constrain subsurface fault geometry and total slip. These parameters, when combined with biostratigraphic ages and tephrachronology for pre-growth and growth strata, bracket the timing of the onset of deformation and provide estimates of average rates of fault slip, shortening and uplift. Quantification of forearc shortening in Northeastern Japan along the Futaba and other forearc faults is necessary to consider the potential influence of a deformable forearc on the magnitude and distribution of offshore subsidence along this erosive margin. Inner forearc shortening may change forearc taper,
induce additional loading of the outer forearc, and shed a sediment load that is sequestered in the subsiding portion of the outer forearc. Therefore, a portion of the outer forearc subsidence record previously interpreted to reflect a local response to tectonic erosion may instead be the result of inner forearc deformation.
Figure 1–1 Digital elevation model and bathymetry of Japan showing tectonic boundaries. The Abukuma Massif is a basement-cored uplift located inboard of the Japan Trench. The trench marks the eastern boundary between the Okhutsk plate, where the Pacific plate subducts nearly orthogonal to the margin at a rate of 82 mm/yr. Elevation data obtained from SRTM3 data set; bathymetry data obtained from ETOPO2 data set.
2 Geologic Background

2.1 Tectonic Setting

The Abukuma Massif is a basement-cored uplift within the inner forearc of northeastern Honshu, inboard of the southern Japan Trench (Figure 1-1). The Japan Trench marks the eastern boundary of the Okhutsk plate, where the Pacific plate subducts near-orthogonal to the plate margin at a rate of 82 mm/yr (Niitsuma 2004, Seno et al. 1993). The Japan Trench terminates in the north at its junction with the Kuril Trench and in the south at the Bonin triple junction (Figure 1-1). Plate reconstructions indicate that this triple junction migrated north to reach its present stable position by the Middle Miocene (Haston & Fuller 1991, Jolivet & Huchon 1989, Jolivet et al. 1994). The crustal thicknesses of the inner forearc of northeastern Japan is on the order of 35-40 km, while the top of the subducting Pacific slab has been imaged at > 50km depth (Hasegawa et al. 1994). Therefore the inner forearc is underlain by mantle wedge and lies inboard of the downward bend in the subduction zone interface.

Subduction along the western Pacific margin initiated during the middle Mesozoic and Cretaceous arc volcanism led to the emplacement of voluminous granodioritic plutons beneath the arc (Hiroi 1998, Iwata 2000). Cretaceous granites have been imaged within the basement beneath the forearc slope cover sequence up to 150 km east of the present-day arc (Finn 1994). Eustatic sea level variations during the late Cretaceous through Oligocene led to the deposition of a terrestrial and marine sedimentary sequence unconformably atop Cretaceous plutons and associated Mesozoic subduction complexes (Mitsui 1971). Early to Middle Miocene (25-15 Ma) backarc extension led to the rifting of the eastern Asian margin, the opening of the Sea of Japan, and the formation of the modern Japan arc (Jolivet et al. 1994, Sato 1991, Sato 1994). Relict Miocene rift-related half-grabens extend across western Honshu and have been recognized as far east as the arcward margin of the Abukuma and Kitakami Massifs (Kato et al. 2006, Sato 1991,
Subsidence of the outer forearc of the northeastern Japan margin initiated in the early Miocene, nearly contemporaneous with Miocene backarc extension, and continued through the Pliocene to present (von Huene & Lallemand 1990). The initiation of outer forearc subsidence in the early Miocene has been documented in multi-channel seismic lines across the Japan trench and outer forearc that image an unconformity separating Paleogene sediments and Cretaceous basement from a Neogene slope sequence, now located 5-6 km below sea level and 15-30 km from the modern trench (Niitsuma 2004, von Huene & Culotta 1989, von Huene et al. 1994). Benthic foraminifera assemblages in sediment cores recovered from DSDP Legs 56, 57, and 87 record deepening waters throughout the Neogene (Arthur 1980, Keller 1980, Nasu 1980, von Huene 1978) and attest to ~6 km of subsidence since 22 Ma (von Huene & Lallemand 1990). Reconstructions of the paleo-margin based on this subsidence record and the position of the subaerial unconformity have been used to estimate average trench retreat rates of ~3 km/Ma and the subsequent removal of 55 km²/Ma of material from the upper plate since the early Miocene (Lallemand et al. 1992, von Huene & Lallemand 1990).

During the late Miocene to early Pliocene, 15-3 Ma, the arc transitioned into a state of compression (Sato 1994). Neogene shortening has been documented across a network of contractional structures in the inner forearc, arc, and backarc of northern Honshu (Sato 1994, van der Werff 2000). A total shortening rate across the arc of 5 km/Ma has been estimated from moment magnitude conversions along faults in northern Honshu (Wesnousky et al. 1984). Two basement massifs, the Kitakami and Abukuma Massifs, are located along the eastern margin of the outer forearc and mark the easternmost, onshore, forearc contractional deformation inboard of the Japan trench (Figure 1-1). The ages of deformed units adjacent to the Futaba fault constrain the uplift of the Abukuma massif to this interval of compression. A number of east-vergent Plio-Quaternary contractional structures in the backarc, arc and innermost forearc have been
interpreted to result from reactivation of listric, Miocene, extensional faults and the inversion of rift-related basins (Kato et al. 2006, Sato 2002). Uplifted marine terraces along the eastern margins of the Abukuma (Suzuki 1989) and Kitakami massifs (Kubo 2002), and modern seismic activity along forearc faults, including the 2008 M7.2 Iwate earthquake which had a focal mechanism consistent with reverse slip along a west-dipping fault, indicate that shortening is ongoing.

2.2 Stratigraphy

The basement of northeastern Honshu consists of Cretaceous plutonic rocks, remnant Paleozoic passive margin rocks, and a middle Mesozoic subduction complex that were rifted from the Asian mainland during Miocene back-arc extension. Basement units are exposed in the hanging wall of the Futaba fault, in the Abukuma Massif (Figure 2-1), and in the core of the Kitakami Massif. Basement units in the forearc of northeastern Honshu are unconformably overlain by a Late Cretaceous through Quaternary sequence of marine and terrestrial conglomerate, sandstone, siltstone, mudstone and volcanic rocks (Kubo et al. 2003, Machida 1999).

The Late Cretaceous Futaba Group and Paleogene Shiramizu Group (Figure 2-2) consist of cyclic sequences of conglomerate, sandstone, mudstone with intercalated coal seams deposited near the paleo-shoreline of the eastern margin of the arc (Mitsui 1971). Lateral changes in sedimentary thickness and lithology within these units in the regions surrounding the southern portion of the Futaba fault are interpreted to reflect the development of three fault-bound sub-basins (Mitsui 1971). The total thickness of late Cretaceous to Oligocene units ranges from 950 to 1100 m (Suto et al. 2005).

The Miocene sedimentary section consists of the Yunagaya, Shirado, Takuku, and Taga Groups and unconformably overlies the Paleogene section (Figure 2-2). These units consist of
alternating sequences of basal conglomerate, sandstone, mudstone and siltstone interpreted to reflect deposition in near shore to shallow marine environments in three fault-bound sub-basins subject to eustatic fluctuations and spatially variable subsidence rates (Kubo et al. 2003, Mitsui 1971). A detailed biostratigraphy (Yanagisawa & Akiba 1998), and interbedded tephras and lahars resulting from widespread Miocene volcanism (Jolivet et al. 1994, Sato 1991) provide age constraints for the section. Fission track ages from tephras at the base of the Yunugaya Group have been dated at 20.8 ±1.2 Ma, and within the Shirado Group at 15.9 ± 0.7 Ma (Suto et al. 2005). Miocene units are deformed in the footwall of the Futaba fault along its entire strike length (Kubo et al. 2003). The total thickness of the Miocene section is 1500 – 2200 m (Kubo 2002).

The Sendai Group lies unconformably atop Miocene units, and consists of nearshore sandstones and mudstones of the Kameoka, Tatsunokuchi, Mukaiyama and Dainenji Formations (Figure 2-2; Suto et al. 2005). The Kameoka, Tatsunokuchi, Mukaiyama Formations straddle the Miocene- Pliocene boundary and are deformed in the footwall of the Futaba fault. Sandstones of the Pliocene Dainenji Formation are deformed in the footwall along the central portion of the Futaba fault, but onlap the fault-related fold at the southern tip of the Futaba fault. Numerous tephras are interbedded in the Sendai Group, and marker horizons are well-mapped east of the Abukuma Massif in the Dainenji and Mukaiyama Formations (Kubo 2002, Machida 1999). A Pliocene tephra stratigraphy has been developed and correlated to an established biostratigraphic framework for the Neogene sediments (Kubo 2002, Machida 1999, Suto et al. 2005), and provides age constraints for the timing of Neogene deformation. The total exposed thickness of the Sendai Group is < 300m (Kubo 2002).
2.3 The Futaba Fault

The Futaba fault system extends for ~150 km along the eastern margin of the Abukuma Massif, from southwest of Sendai to northeast of Iwake (Figure 2-1). It is the easternmost onshore fault in a system of Neogene contractional structures that deform the Neogene cover sequence and places Cretaceous granites that core the Abukuma Massif in fault contact with the sedimentary cover sequence. The strike length of the fault, the absence of Neogene strata in the hanging wall, and the presence of overturned strata in the footwall suggest that the Futaba fault is a major forearc contractional structure and may be an important contributor to the total forearc shortening and uplift budget.

Previous tectonic studies of the regions surrounding the Abukuma Massif have reported fault ramp angles ranging from 35º to 90º for the Futaba fault (Fukushimaken 1999, Mitsui 1971) and both left-lateral and minor reverse displacement (Fukushimaken 1999, Kubo et al. 2003, Mitsui 1971). The Futaba fault zone parallels a Cretaceous, mid-crustal, sinistral shear zone containing mylonites and cataclasites overprinted by Neogene gauge and breccia (Ohtani et al. 2004, Tomita et al. 2002). A Paleogene to early Neogene history of extensional faulting near the southern tip of the Futaba fault is inferred from segmentation of the sedimentary section into at the southern terminus of the Futaba fault into minor fault-bound sub-basins. Neogene displacement has been interpreted to reflect reactivation of these earlier structures, with an estimated 200m or less of throw along the fault (Mitsui 1971).

Fault characterizations by the Active Faults Research Center of Japan classify the modern Futaba fault as a sub-vertical (80ºW-90º) fault with dominant left-lateral slip (Kubo et al. 2003) but field data exist for only the central segment of the fault. The Futaba fault is divided into three behavioral segments: the southern Namie segment, the central Haramachi segment, and the northern Watari segment (labels a - c in Figure 2-1). Quaternary ruptures are recognized along only the Haramachi segment, where late Pleistocene and Quaternary alluvium is offset, producing
a 1.2m high east-facing scarp (Fukushimaken 1997, 1999, Kubo et al. 2003). Ruptures at 2,400 and 10,000 yr BP are reported from a trench across the fault near Soma, and offset deposits yield a left lateral slip rate of 0.1 mm/yr and a dip slip rate of 0.05-0.1 mm/yr (Fukushimaken 1997, 1999). The northern and southern fault segments are not categorized as active; however, their continuity with the active Haramachi segment and the presence of a deeply incised, steep, linear mountain front along the entire fault suggests the potential for Quaternary activity.
Figure 2–1 Simplified geologic map of the Abukuma Massif (after Kubo et.al., 2003), bound on the east by the Futaba fault. The Futaba fault is divided into the a) Namie segment b) Haramachi segment and c) Watari segment. The massif is cored by Cretaceous granites and older sedimentary and metasedimentary units. Along the Eastern flank of the Abukuma massif, stream cuts expose deformed Paleogene and Neogene strata along the footwall of the Futaba fault. Boxes denote locations of inset geologic maps along modeled profiles in Figure 3-1.
Figure 2–2 Stratigraphic column for the eastern flank of the Abukuma Massif (after Kubo et al, 2002).

<table>
<thead>
<tr>
<th>Age</th>
<th>Group</th>
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<td>Dainenji Fm</td>
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<td></td>
<td>Kameoka Fm</td>
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<tr>
<td>Middle &amp;</td>
<td>Takuku Gp</td>
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<tr>
<td>Late Miocene</td>
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<td>Ashizawa Fm</td>
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</table>
3 Field Observations and Motivation for Study

New field observations and re-interpretation of existing geologic maps provide evidence to suggest that the Futaba fault is an active, steeply west-dipping reverse fault. Vegetative cover and retaining structures along road and stream cuts limit the continuous exposure of the fault. However, several stream cuts and coastal outcrops in the cover sequence provide exposures of the fault-related fold, and quarries in the crystalline rocks of the Abukuma Massif provide exposures of sheared and brecciated rocks within the fault zone.

The Futaba fault places crystalline basement in fault contact with folded Cretaceous through Pliocene sedimentary rocks along ~150 km of strike length. The cover sequence is preserved in the hanging wall of the Futaba fault only at the southern tip of the Namie segment, where the Futaba fault is blind and the Cretaceous through Miocene section is folded into an open, gently southward-plunging, hanging wall anticline (Figures 2-1, 3-1A). Bedding dips increase from ~5ºE in the gently-dipping western limb of the fold to sub-vertical or overturned in the steeply-dipping eastern limb of the hanging wall anticline (Figure 3-1A). Bedding dips in the steep forelimb range from ~60ºE to 60ºW along strike, but at any given cross section, bed dips within the Miocene and older section are constant over short (100m) spatial scales. These units are here considered pre-growth strata that predate deformation of the fault-related fold.

Miocene rocks in the forelimb of the anticline are unconformably overlain by newly identified Pliocene growth strata within the Dianenji Fm (Figure 3-2). Bedding dips in the Pliocene section decrease to the east from ~60ºE directly above the unconformity to sub-horizontal over a distance of ~150m (Figure 3-2). The timing of initiation of slip along the Futaba fault is bracketed by the age of the pre-growth – growth transition. The progressive upslope decrease in bed dips in the growth section record the incremental deformation of the fault-related fold. Multiple tephra horizons are interbedded in the both the pre-growth and growth section and provide age constraints to bracket the onset and rates of deformation.
The hanging wall anticline is disrupted by a diffuse zone of minor reverse faults with displacements averaging less than 50 m (Kubo et al. 2003, Mitsui 1971). This zone transitions northward into a pair of sub-parallel splays that merge with the Futaba fault (Figure 3-1A). The eastern splay places overturned Miocene beds of the Yunagaya Group in the forelimb of the hanging wall anticline on top of gently east-dipping beds of the Pliocene Dainenji Formation, and has a minimum stratigraphic separation of 300m (Figure 3-3). Other measured minor faults in the region have dips ranging from 35° to 85°.

The northward transition of the Futaba fault from blind to emergent is expressed in the landscape by the emergence of a steep, linear mountain front, an increase in the average elevation of the massif, and an increase in hanging wall relief (Figure 3-4). The change in mountain front morphology generally coincides with the southernmost mapped location of the Futaba fault. In addition, high hill slope gradients and deeply incised channels are restricted to an ~10-15 km region adjacent to the Futaba fault. These observations suggest that the Futaba fault has been active during the Quaternary.

The fault contact between Cretaceous basement and the sedimentary cover sequence does not outcrop, but Riedel shears exposed in a quarry in the fault zone are consistent with slip along a steep, west-dipping reverse fault (Figure 3-5). The most common shear plane orientation has a west dip of 50°-60°, and offset markers indicate top to the east displacement. A slickenline with a rake of 70° from the north was measured on a shear plane with an orientation of 190° 54°W, which is consistent with a small left-lateral component in addition to dip slip.

The Pliocene units that comprise the growth strata at the southern tip of the Futaba fault are folded into a regionally extensive footwall syncline that extends along the northern ~40km of the Namie segment (Figures 3-1B & 3-6). The Dainenji Formation and older units in the Sendai Group are deformed into a regionally-extensive, open footwall syncline that extends along nearly the entire strike length of the Namie segment (Figure 3-6). Dips in the western limb of the
footwall syncline range from 60ºE to 70ºW and dips in the eastern limb are sub-horizontal. Only the uppermost Miocene section and the lower Pliocene section of the Sendai Group outcrop within the steep limb of the footwall syncline.

The Haramachi segment of the Futaba fault is continuous with the Namie segment, but the character of the footwall changes northward along strike. The sedimentary section in the footwall thins toward the north, and Pliocene units lie sub-horizontally atop of Mesozoic accretionary prism units along the Haramachi segment (Figure 2-1). In contrast to the Namie segment, the Futaba fault along the Haramachi segment places Cretaceous basement in fault contact with Mesozoic units. The Pliocene section is absent in both the hanging wall and the footwall immediately adjacent to the fault, and therefore no fault-related folds are present.

The Futaba fault steps east from the Haramachi to the Watari segments (Figure 2-1) where the fault bounds a linear ridge of Cretaceous basement, the Wariyama uplift, on the east. At the southern tip of the Watari segment, steeply dipping (60º-80º) Miocene beds of the lower Sendai Group are unconformably overlain by gently dipping (30ºE) Pliocene units of the Dainenji Fm. The Pliocene section is steeply dipping adjacent to the fault along its entire length, and is analogous to the footwall syncline along the Namie segment. Toward the northern limit of the Abukuma Massif, displacement along the Watari segment dissipates into an anticline developed in Miocene volcanic rocks in the hanging wall of the fault.

The above field observations suggest that the Cretaceous granites that core Abukuma Massif are in the hanging wall of a west-dipping, basement-involved reverse fault, in contrast to previous mapping and geologic reports that cite the Futaba fault as a sub-vertical left-lateral fault (AIST 2008, Fukushimaen 1999, Kubo et al. 2003). Significant reverse slip is supported by east-vergent fault related-folds, west-dipping reverse shear planes in the fault zone, and the absence of the sedimentary cover sequence in the hanging wall. While the fault plane itself does not crop out, a steep, west-dipping fault is consistent with the linearity of the fault trace in map-
view, the dip of shear planes and minor faults, and with its proximity to other steeply-dipping reverse faults north of the Futaba fault (Kato et al. 2006).

This study uses modeling of fault-related fold geometry to place constraints on the most likely ranges for fault ramp angle and total dip displacement for the Futaba fault. Limited exposures of the Futaba fault zone preclude direct measurements of ramp angle and kinematic indicators of fault slip. However, folds associated with the Futaba fault have been mapped along its entire strike length (Yanagisawa & Akiba 1998) and are well-exposed at several outcrops. Fault-related fold modeling is used here to predict a sub-surface fault and fold geometry consistent with observed fold geometry along a topographic profile and to place constraints on the fault ramp angle and total slip along the Futaba fault.
Figure 3–1  Detail geologic maps at locations of modeled transects across the hanging wall anticline (A.) and the footwall syncline (B.). See figure 2-1 for locations.
Figure 3–2 Miocene pre-growth units of the Yunagaya Group are unconformably overlain by Pliocene growth strata of the Dainenji Formation of the Sendai Group at the southern tip of the Futaba fault. See Figure 2-1 for location.

Figure 3–3 Overturned Miocene beds of the Yunagaya Group are in fault contact with shallowly east-dipping Pliocene beds of the Dainenji Formation along a splay of the Futaba fault. See Figure 2-1 for location.
Figure 3–4 Panoramic view of the Abukuma Mountain front at the southern tip of the Futaba fault. Note the increase in hanging wall elevations and relief where the Futaba fault becomes emergent. See Figure 2-1 for location.
Figure 3–5 Reidel shears exposed in a quarry in the Futaba fault zone consistent with top to the east shear within a west dipping fault zone. See Figure 2-1 for location.

Figure 3–6 Footwall syncline developed in the Dainenji Formation along the Namie segment of the Futaba fault. See Figure 2-1 for location.
4 Methods

Trishear is a fault-propagation fold model first proposed to describe the deformation associated with basement-involved thrusts, such as the Laramide fault-propagation folds of the western United States (Erslev 1991). The model has been used as an alternative to kink band fold kinematics to explain the downward tightening and convergence of fold hinges and changes in stratigraphic thickness and limb dip observed in basement-involved, fault-related folds, (Allmendinger 1998, Erslev 1991). The model simulates deformation by allowing distributed simple shear within a triangular shear zone that propagates with the fault tip.

The Futaba fault and the Abukuma Massif northeastern Honshu, Japan, exhibit several characteristics in common with Laramide-style structures that suggest trishear as a suitable model for the Futaba fault-related folds. These include: 1) involvement of crystalline basement in the hanging wall of the thrust, 2) a relatively sharp fault that places crystalline basement in contact with the sedimentary cover sequence, and 3) a diffuse zone of deformation and folding within the cover sequence. In addition, deformation produced by the trishear kinematic model is well-matched by mechanical models that simulate basement-involved folds based on viscous folding theory for a homogenous, isotropic body (Cardozo 2003, Johnson & Fletcher 1994, Johnson & Johnson 2002). Mechanical and kinematic models for basement structures have been shown to produce comparable deformation patterns within homogeneous, weak materials (Hardy & Finch 2006), such as the poorly consolidated sediments that constitute the cover sequence of the Abukuma Massif.

4.1 The Trishear Kinematic Model

Kinematic modeling was performed using a MATLAB program designed for this study (Appendix A) that simulates deformation based on the forward modeling approach presented in (Allmendinger 1998) and Zhender and Allmendinger (2000) and the velocity field solutions
presented in Zhender and Allmendinger (2000). The velocity of a point is here defined as the difference in particle position divided by a model time step \((t_{step})\). The trishear kinematic model for fault-related folds produces simple shear within a triangular zone ahead of a propagating fault tip in a domain bound by a fixed footwall \((v=0)\) and a hanging wall with a velocity equal to a fault slip rate, \((v=v_o)\) over a given time step (Figure 4-1; Erslev, 1991; Allmendinger, 1998). This model solves for a velocity field that describes the 2-D deformation of an incompressible material confined to a shear-zone of angular area \(\phi_1+\phi_2\), whose apex is fixed to the propagating fault tip (Figure 4-1). Material in the footwall and hanging wall outside of this shear zone are not internally deformed, but have a uniform velocity field. Material within the shear zone is deformed such that area is conserved, or the divergence of the velocity field within the shear zone is zero:

\[
\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = 0 \tag{1}
\]

This model assumes no out-of-plane material transfer and results in area-balanced cross sections. The shear zone is bound by a lower, zero-velocity boundary condition,

\[
v_x = v_o \quad \text{and} \quad v_y = 0 \quad \text{on} \quad y = x\tan\phi_i \tag{2}
\]

and an upper velocity boundary condition defined by the slip rate (Figure 3-1),

\[
v_x = v_o \quad \text{and} \quad v_y = 0 \quad \text{on} \quad y = -x\tan\phi_2 \tag{3}
\]

The velocity field solution used herein assumes homogenous trishear, such that \(\phi_1=\phi_2=\phi\), and uses a \(v_x\) field that varies with \(\sin(y)\) at the upper velocity boundary (Zehnder & Allmendinger 2000). This solution allows for smooth changes in the velocity field at the upper boundary (Zehnder & Allmendinger 2000) and produces convex rather than concave folds within the shear zone. At time \(t=t_i\), the 2-D velocity field within the shear zone that satisfies the above assumptions and equations 1-3 is prescribed by:
\[ v_x = \frac{1}{2} v_o \left[ \sin \beta + 1 \right] \]

\[ v_y = v_o \tan \phi \left[ \cos \beta + \beta \sin \beta - \frac{\pi}{2} \right] \quad (4) \]

where \( \beta = \beta(x, y) = \left( \frac{y \pi}{2x \tan \phi} \right) \) (Zehnder & Allmendinger 2000).

### 4.2 Simulation of Deformation

Resultant fold form is controlled by the geometry of the triangular shear zone and the rate and direction in which it propagates through the deforming media. This is dictated by six model parameters: 1) \( \phi \), the angular width of the shear zone, or the trishear angle, 2) \( \alpha \), the fault ramp angle, 3) \((tipx, tipy)\), the x and y coordinates describing the position of the fault tip, 4) \( v_o \), slip rate, or hanging wall velocity, 5) \( P/S \) ratio, the ratio of the rate of fault tip propagation to the slip rate, and 6) \( t_{\text{final}} \), the total time elapsed during deformation (Figure 4-1). The number of free parameters is reduced in the model implemented here by combining \( v_o \) and \( t_{\text{final}} \) into a single parameter \( S \), or total slip, where \( v_o t_{\text{final}} = S \) for a constant \( v_o \) and variable \( t_{\text{final}} \). Because there is a linear relationship between the \( v_o \) and \( t_{\text{final}} \) and because there is no time dependence on the velocity field in the model, the product of \( v_o \) and \( t_{\text{final}} \) recovers the true value for \( S \). If either \( v_o \) or \( t_{\text{final}} \) are independently known, the other parameter can be calculated.

The deformation resulting from slip along a reverse fault is simulated by tracking particle paths for initially horizontal marker horizons by numeric integration of the velocity field prescribed by eq. (4) as it moves along a path dictated by \( \alpha \) and \( P/S \), from time \( t=0 \) to \( t=t_{\text{final}} \). The velocity field is solved at time \( t \), according to the velocity field in eq. (4) and the boundary conditions eq. (2) & (3), in a coordinate system where the x-axis is parallel to the fault ramp and the fault tip has the coordinates \( x=y=0 \) (Figure 4-1). This coordinate system propagates with the fault tip at a rate dictated by the \( P/S \) ratio along the fault ramp. The tip-centered velocity field in
the x,y coordinate system is rotated by $\alpha$ and translated along the fault by $P/S(v, t)$ into an $i_j$ coordinate system where the $i$-axis is parallel to the earth’s surface (Figure 3-1). Particle paths and resultant deformation are tracked in the $i_j$ coordinate system by numeric integration of the velocity field from time $t=0$ to $t=t_i$.

The model used in this study was validated against an existing forward trishear modeling program, Fault Fold© (Allmendinger 1997-2007), which is based on the velocity field solutions presented in section 4.1. The MATLAB code replicates the resultant deformation produced using Fault Fold© for the same set of input parameters with minimal misfit. The code used in this study has the following advantages over the existing algorithm: 1) ability to run batch forward models, 2) ability to add growth strata at a given sedimentation rate, 3) no limitations on the number of modeled beds, 4) the fit between model fits to observed data is not restricted to the built-in statistics of Fault Fold©, but can be assessed by any appropriate statistical metric.

4.3 Model Setup and Selection of Parameter Space

Forward models were run to simulate the deformation of initially planar, gently seaward-dipping strata overlying rigid basement containing a planar fault. Initial stratigraphic thicknesses were constrained from measured sections (Suto et al. 2005), and where available, from core data (Kubo 2002). The total thickness of the Cretaceous through Pliocene sedimentary section at section A-A’ at the southern tip of the Futaba fault (Figures 2-1 & 3-1A) ranges from 2200-3000m. A most likely thickness of ~2800 m is used in the model of section A-A’. The thickness of the sedimentary section at section B-B’ across the footwall syncline (Figures 2-1 & 3-1B) is poorly constrained. The minimum thickness is ~800m, based on extrapolation of unit thickness and depth to basement in cores from 20 km south of the modeled section, but could be as thick as ~2200m (Kubo 2002). A mean sedimentary thickness of 1500m is used in the model of section B-B’.
The two trishear parameters necessary to calculate rates of fault slip, uplift, and shortening are fault ramp angle ($\alpha$) and total slip ($S$), calculated as the product of $v_o$ and $t_{\text{final}}$. To determine the best values for $S$ and $\alpha$, Monte Carlo simulations were run for a range of $\alpha$, $\phi$, $P/S$, $tipx$, $tipy$, and $t_{\text{final}}$ to determine parameter values that produce a fold geometry consistent with observed bedding positions along a surface transect at the southern tip of the Futaba fault.

Input values for Monte Carlo simulations of the transect across the hanging wall anticline at the southern tip of the Futaba fault were initially randomly selected from uniform prior distributions (Table 4-1). Minimum and maximum bounds for ramp angle (30º-89ºW) were chosen to span the ramp angles of 35 to 70º and 80º to 90º proposed in previous tectonic studies of the regions surrounding the Abukuma Massif (Fukushimaken 1999, Mitsui 1971) as well as the 50º to 70º ramp angle suggested by field observations. Minimum and maximum bounds for $\phi$ (40º-130º) and $P/S$ (0.5-3.5) were selected based on preliminary results from prior model runs.

The position of the initial fault tip was calculated from fault ramp angle and present-day fault-tip position. The range of depths for initial fault tip position, $tipy$, was selected to be no shallower than the base of the sedimentary cover sequence, and minimum and maximum bounds (-4400m to -2700m below sea level) were constrained by results from prior model runs. The position of the present day fault tip along section A-A’ can be constrained by projecting the tipline defined by the southernmost known outcrop of the Futaba fault south along strike into the plane of the modeled section. Uncertainties on fault tip position in the section define bounds for the present day x-coordinate of the fault tip to within 2km of the coastline. A present-day x-coordinate of the fault tip was randomly selected from this range and used in combination with fault ramp angle and initial depth of fault tip ($tipy$) for each Monte Carlo simulation to calculate the x-coordinate of the initial fault tip, $tipx$.

Forward models of the hanging wall anticline at section A-A’ were run for 30,000 combinations of input parameters for multiple values of total slip ranging from 1200-4000 km in
50m increments (Table 4-1), resulting in a total of ~1.5 million fold simulations. The range of total slip was selected to bracket the range of slip required to exhume the basement-cover contact given the maximum allowed depth of the initial fault tip and uncertainties in the total thickness of the sedimentary section.

The ranges of input trishear parameter values that simulate folds that reproduce the observed dip data to within the criteria discussed below in section 4.4 were used to constrain the distributions of input parameters for a second set of models. In the second set, models were run using uniform distributions for total slip, propagation to slip ratio, and fault tip position, and gaussian distributions for ramp angle and trishear angle based on the mean and standard deviation of best-fit results from the first round of models (Table 4-1). Forward models were run for 20,000 combinations of input parameters for multiple values of total slip ranging from 1500-3000 km in 50m increments, resulting in a total of ~1 million fold simulations.

A second section across the footwall syncline at section B-B’ was similarly modeled. Identical uniform parameter bounds for $\phi$ (40º-130º) and P/S (0.5-3.5) were used (Table 4-1). Because of the large uncertainties on the sediment cover thickness along this section, the depth range of the initial fault tip, tipy (2500-0m below sea level) was not restricted to the inferred depth range of the basement-cover contact. The x-coordinate of the present day surface trace of the Futaba fault is constrained to a 500m window between the closest known outcrops of the Mukaiyama Formation of the Sendai Group in the footwall and crystalline basement in the hanging wall of the fault.

Ramp angles for model of the footwall syncline along section B-B’ were randomly chosen from the Gaussian distributions of most-likely ramp values obtained from modeling of the hanging wall anticline (Table 4-1). Forward models of the footwall syncline were run for 5,000 combinations of unique parameters for total slip ranging from 50m-1.5 km in 50m increments.
The range of total slip for this section was similarly based on the uncertainties in initial fault tip position, total thickness of the sedimentary cover, and from prior model runs.

4.4 Determination of a Best-fit Model

Best-fit ranges for fault ramp angle and total slip were determined from trishear model parameter sets that produce a subsurface fold and fault geometry that minimizes the misfit between observed bed dips and output model slopes along a surface profile (Figure 4-2). The assessment of model fit was restricted to bedding data from the pre-growth section along a topographic profile due of a lack of independent geophysical or borehole data that could constrain sub-surface bed dips. Structural data were collected from two sections across the hanging wall anticline that span the pre-growth – growth transition at the southern tip of the Futaba fault, and from two sections across the footwall syncline ~40 km north of the southern fault tip. A combination of new field bedding data in the growth section and existing map data in the pre-growth section along section A-A’ (Figures 2-1 & 3-1A) were used to constrain forward models of the hanging wall anticline. New field bedding data from the northern transect along section B-B’ were used to constrain forward models of the footwall syncline (Figure 3-1B).

A root mean square (RMS) fit was calculated for each unique combination of $tip_x$, $tip_y$, $P/S$, $\phi$, $t_{final}$ and $\alpha$ based on the residuals between observed bed dips and output model bed slopes. Resultant model RMS values, therefore, reflect the average deviation between observed and modeled bed dips. Given that observation error on bed dips is approximately $\pm 5^\circ$, any set of model parameters that produced a RMS fit $\leq 5^\circ$ was considered an acceptable fit because it could reproduce the observed data within error. Best-fit parameter ranges were determined for a section across the hanging-wall anticline from models with RMS$<5^\circ$ to constrain total slip and fault ramp angle at the southern tip of the Futaba fault segment. These parameter ranges were used as model
inputs for a second section across the footwall syncline along the northern portion of the Namie segment, to place constraints on slip and ramp angle for the central portion of the fault.

4.5 Stratigraphic Ages and Deformation Rates

The time of onset of slip along the Futaba fault is bracketed by dated horizons, determined from existing tephrachronology and biostratigraphy, in the growth and pre-growth strata at the southern tip of the Futaba fault. A minimum age of fault initiation is obtained from the age of tephra horizon SF4.5 near the base of the growth section Dainenji Fm, upper Sendai Group. Similarity in petrographic characteristics and chemical composition and a detailed Pliocene microfossil biostratigraphy have been used to correlate SF4.5 to the 3.95 ±0.2 Ma An85 bed of Znp-Ohta ash (Nagahashi 2004). A maximum age of fault initiation is obtained from a tephra horizon near the top of the pre-growth section in the lower Sendai Group, which is chemically correlated to a tephra with a zircon/fission track age of 5.6±0.5 Ma in the Kameoka Formation (Oishi et al. 1998). Average rates of fault slip, uplift, and shortening were calculated for best-fit fault ramp angles using optimal values for total slip, assuming slip initiated between 5.6±0.5 and 3.95 ±0.2 Ma and has continued to the present.
Figure 4–1  Setup for the velocity field solution to the trishear kinematic model for fault-related folds (after Zhender and Allmendinger, 2000). Deformation results from distributed simple shear within a triangular zone of width $\phi_1 + \phi_2 = \phi$, that is bound by $y = x \tan \phi$ and $y = -x \tan \phi$ and is fixed to a propagating fault tip ($\text{tip}_x$, $\text{tip}_y$). The velocity field is solved for an $x, y$, coordinate system parallel to the fault ramp angle $\alpha$ and fixed to the fault tip. The velocity field propagates with the fault tip at a rate of $P/S (v_o, t)$ along the fault ramp, within an X’, Y’ coordinate space. Red arrows denote velocity field at time $t$. 
Figure 4–2 Schematic of the observed data and determination of best-fist trishear models, as described in the text. A) Observed bedding dip data \((x_i, y_i, \theta_i)\) gathered from folded sedimentary rocks along a surface profile. B) Quality of fit for a set of model parameter values is based on the RMS fit between observed bed dips and model bed slopes. Fault ramp angle \(\alpha\) and total slip \(S\) are estimated from the range of best fit parameter values.
Table 4-1 Input parameter distributions used for Monte Carlo simulations of fold geometry along sections A-A’ and B-B’.

<table>
<thead>
<tr>
<th>Trishear Parameter</th>
<th>Section A-A’</th>
<th>Section B-B’</th>
<th>Range of Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range of Inputs</td>
<td>Range of Inputs</td>
<td>Range of Inputs</td>
</tr>
<tr>
<td>Total Slip (S)</td>
<td>1200 to 4000 m</td>
<td>1500 to 3000 m</td>
<td>50 to 1500 m</td>
</tr>
<tr>
<td>Ramp angle (α)</td>
<td>30° to 89°</td>
<td>69° ± 10°</td>
<td>68 ± 7°</td>
</tr>
<tr>
<td>Trishear angle (φ)</td>
<td>40° to 130°</td>
<td>98° ± 10°</td>
<td>40° to 130°</td>
</tr>
<tr>
<td>Propagation to slip ratio (P/S)</td>
<td>0.5 to 3.5</td>
<td>0.6 to 2.2</td>
<td>0.5 to 3.5</td>
</tr>
<tr>
<td>Initial fault tip position (y)*</td>
<td>-4400 to -2700 m</td>
<td>-4400 to -3300 m</td>
<td>-2500 to 0 m</td>
</tr>
<tr>
<td>Final fault tip position (x)#</td>
<td>-2000 to 200 m</td>
<td>-1000 to 200 m</td>
<td>-6200 to -5500 m</td>
</tr>
</tbody>
</table>

* meters below sea level
# 0 m at coastline
5 Trishear Model Results

5.1 Hanging Wall Anticline

Monte Carlo simulations of forward trishear kinematic models of a section across the hanging wall anticline (Figure 3-1A) constrain the most likely ramp angle and total slip for the Futaba fault and define a range of optimal trishear angles, P/S ratios, and fault tip positions that simulate the observed fold. Of the approximately 1 million simulations from the second round of models, 638 models resulted in a fold geometry that reproduced observed bed dips to within an RMS of <5°. The frequency of the occurrence of values for ramp angle, trishear angle (φ), P/S ratio, and initial fault tip position approach Gaussian distributions centered on parameter values that simulate the most likely fault-related fold.

Model fault-related folds that replicate observed bedding with an RMS of <5° have a most likely ramp angle of 68±7° (Figure 5-1a; Table 5-1). A best-fit model with a minimum RMS of 2.0° is produced for a ramp angle of 65° (Figure 5-2 A) and acceptable ramp angles range from 50° and 88° (Figure 5-2 B&C). Exploration model folds produced using a wide rage of trishear parameters values show that the observed bedding data can be reproduced for ramp angles outside this optimal range. However, slip along very gentle (35°-45°) or very steep (80°-90°) ramps can only reproduce the observed fold for a very narrow range of parameter values for φ, P/S, total slip, and tip position. Simulated folds produced for ramp angles of 35°-45° generally underestimate the position of the basement-cover contact, while ramp angles >80° generally overestimate it.

Total dip slip required to produce model folds that replicate observed bedding ranges from 1900-2600m (Figure 5-2 C&D), with a mean of 2168±136m (Figure 5-1b; Table 5-1). Total slip required to simulate the hanging wall anticline is dependant on the total thickness of the sedimentary section and the initial position of the fault tip. The total sedimentary cover thickness
is not a parameter that is constrained by the trishear model but must be estimated a priori from measured sections. The total amount of slip required to exhume the basement-cover contact is directly dependent on the initial depth of the contact prior to deformation. Therefore, the thickness of the sedimentary section is the primary limit on the range of total slip required to simulate the observed bedding orientations.

The initial fault tip position, however, is a free parameter that can be constrained by the model. Initial tip position is here interpreted to reflect the position of the fault tip at the point at which trishear-like deformation commences. Fault propagation may occur before this point, but with minimal deformation of the cover sequence, such as would be the case for a very rapidly propagating fault or for a fault tip that is located far from the base of the deformed section. Alternately, the initial tip position may reflect the tipline of a pre-existing fault that becomes reactivated. In either case, trishear kinematics would not describe the evolution of the system prior to this point.

Best-fit models of the hanging wall anticline have fault tip positions that range in depth from 2700-4400m below the surface (Figure 5-3), which brackets the inferred depth to the basement-cover contact of ~3000m. Optimal initial fault tip depth varies with fault ramp angle such that models simulated for steeper ramp angles require a shallower initial fault tips. The optimal range of initial fault tip positions that produce simulated folds with minimal RMS misfit (<3°) lies in a narrow range between 3500-4000m below the surface. This depth range is located approximately 1000m below the inferred basement-cover contact.

The Futaba fault is blind beneath the hanging wall anticline at the southern tip of the Namie segment, but best-fit fault related fold models predict a relatively narrow range of present-day (final) fault tip positions along this section. For RMS<5°, the model predicts possible fault tip positions within 1000m of the surface and within a 1000m wide map-view window (Figure 5-3; Table5-1). For simulated folds with an RMS misfit <3°, the range of predicted fault tip
positions narrows to a 300m-wide window in map view within 250m below the surface. The model predicted fault tip position is consistent with the projected position of the fault tip in map-view from the southernmost known outcrop of the Futaba fault.

Limb dips and interlimb angles of simulated folds are governed by the trishear angle (φ) and the P/S ratio, for a given ramp angle and total slip. Best-fit models of the hanging wall anticline with RMS<5° have trishear angles of 72°-125°, with a mean of 95°±8°, and P/S ratios of 0.68-2.19, with a mean of 1.6±0.3 (Figure 5-4; Table 5-1). The two parameters directly correlate such that the same model fold geometry can be simulated for a range of combinations of φ and P/S - large values for both φ and P/S can produce the same simulated fold geometry as a small values for φ and P/S. A geologic cross section across the hanging wall anticline based on best-fit models is presented in Figure 5-5A.

5.2 Footwall Syncline

Best-fit ranges for trishear parameter were also determined for a second section across the footwall syncline, along line B-B’ (Figure 3-1B). Monte Carlo simulations of this section selected ramp angles from the Gaussian distribution of fault ramp angles (68±7°) determined from models of the hanging wall anticline. Of the approximately 500,000 simulations run, no models resulted in a fold geometry that reproduced observed bed dips to within an RMS of <5°. Results were therefore inspected for 113 models with an RMS <10°.

The most likely fault ramp angle for the footwall syncline section is 60±9.3° (Table 5-1), which has a shallower mean ramp angle than the input range 68±7° obtained from models of the hanging wall anticline (Figure 5-6). The footwall syncline is fit by tighter trishear angles (64±21°) than the hanging wall anticline (Table 5-2), which implies that the fold would also be fit
by high P/S ratios. However, model results for all tested P/S ratios are equally as likely and provide no direct constraints on this parameter.

Total slip and initial fault tip position are poorly constrained by models of the footwall syncline because there are no marker horizons of known position in both the hanging wall and footwall to limit the maximum allowable slip and because of the large uncertainty in the thickness of the sedimentary section. However, vertical beds in the Goyasu Fm are present in the hanging wall of the Futaba fault just north of the modeled section (Figure 3-1B). This suggests a minimum stratigraphic separation of 1500-1700m for the Goyasu Fm across the Futaba fault at this location. Most likely model values for fault slip along this section are also minimum estimates, because slip can occur without further limb rotation in the trishear model once the fault tip propagates beyond the measured section. The observed dip data can be fit by models with at least 500-1000m of slip, but are best fit by models with minimal slip and initial tip positions <500m below the surface. These fault tips positions are much shallower than the range obtained from models of the hanging wall anticline and from stratigraphic separation of the Goyasu Fm. This suggests that the fault may have propagated rapidly to near the top of the cover sequence prior to the deposition of the Pliocene units deformed within the footwall syncline. A geologic cross section across the footwall syncline based on best-fit models is presented in Figure 5-5B.

5.3 Deformation Rates

The time of the onset of deformation is bracketed by dated tephra horizons in the growth and pre-growth strata within the hanging wall anticline. Best-fit values for dip slip of 2.17±1.4 km and fault ramp angle of 68±7º, obtained from models with RMS<5º, are combined with a time of onset of deformation of 5.6±0.5 and 3.95 ±0.2 Ma to calculate average dip slip, uplift, and shortening rates from the time of fault initiation to the present. The best-fit geometry and total
dip slip predict total uplift of 2010±160 m and total shortening of 810±50 m. Combining these values with a minimum and maximum age of initiation of fault slip yields slip rates between 0.39±0.05 to 0.55±0.05 mm/yr, uplift rates of 0.36±0.05 to 0.51±0.05 mm/yr, and shortening rates of 0.15±0.02 to 0.2±0.02 mm/yr (Table 5-2).

Previously published slip rates have been obtained from a trench across the Haramachi segment of the Futaba fault (Figure 2-1) approximately 30 km to the north of the modeled section B-B’. The average dip slip rate since the Pliocene obtained from modeling of the Namie segment of 0.39-0.55 mm/yr is five to ten times greater than the reported dip slip rate of 0.05-0.1 mm/yr obtained from offset Quaternary deposits along the Haramachi segment (Fukushimaken 1999; Table 5-2). Stage 5e marine terrace treads preserved in the hanging wall of the Futaba fault south of section A-A’ are at elevations of ~60 m above sea level (Kioke & Machida 2001). Extrapolation of nearby strandlines predicts minimum elevations for stage 5e strandlines of 60-70 m above sea level in the Futaba hanging wall and minimum Quaternary uplift rates of 0.5-0.6 mm/yr (Suzuki 1989). These quaternary uplift rates agree well with the 0.36-0.51 mm/yr uplift rates determined from best-fit models (Table 5-3). These results suggesting that trenching-derived Holocene slip rates may underestimate geologic average slip rates.
Figure 5–1 Most likely distributions of fault ramp angle and total slip for models of the hanging wall anticline along section A-A’. Histogram represent the frequency at which the selected parameter values result in a model fold that can reproduce observed bedding data with an RMS <5°. Superimposed curves represent Gaussian distributions for the mean and standard deviation for fault ramp and total slip given RMS cutoff values of 5°, 4° and 3°.
**Figure 5–2 A.** Best-fit trishear model for the hanging wall anticline along section A-A’. Top: Bedding dips in the exposed Miocene pre-growth strata (blue dip tabs) are used to constrain the most likely fault ramp angle, total slip, fault propagation to slip ratio (P/S), trishear angle (phi) and initial fault tip position for the Futaba fault. Bottom: Residuals between model bed dips and observed bed dips used to calculate RMS misfit for the best-fit model. Continued on following page.
Figure 5-2 B.-D. Examples of allowable model folds that replicate observed bedding dips with an RMS<5.  B. Fold with minimum allowable fault ramp angle.  C. Fold with maximum allowable fault ramp angle.  Note that a vertical ramp cannot produce beds overturned by more than ~10º.  D. Fold with minimum allowable slip.  E. Fold with maximum allowable slip.
Figure 5–3  Range of initial and final fault tip positions that can reproduce bedding data for the hanging wall anticline along section A-A’ with an RMS<5º. Fault tip positions are contoured to show the minimum RMS value for a given fault tip coordinate. Solid line represents the most likely fault ramp angle, and dashed lines bound the range of fault ramps that can produce a model with RMS<5º.

Figure 5–4  Range of propagation to slip ratios (P/S) and trishear angles (ϕ) that produce a fold that replicates observed bedding data with an RMS<5º for the hanging wall anticline along section A-A’. P/S and ϕ are contoured to the minimum RMS value for a given parameter pair.
Figure 5–5 Cross sections across the hanging wall anticline along section A-A’ and the footwall syncline along section B-B’, based on results of trishear modeling. See Figures 2-1 and 3-1 for locations.
Figure 5–6 Most likely distributions of fault ramp angle and total slip for models of the footwall syncline along section B-B’. The histogram and superimposed Gaussian distribution for the mean and standard deviation of the population show the frequency at which the ramp angle results in a model fold that can reproduce observed bedding data with an RMS $<10^\circ$. 
Table 5-1 Mean and standard deviation for best-fit trishear model parameters obtained from Monte Carlo simulations of the hanging wall anticline at section A-A’ and of the footwall syncline at section B-B’ (see Figures 2-1 & 3-1 for location).

<table>
<thead>
<tr>
<th>Trishear Parameter</th>
<th>A-A’ RMS &lt;5</th>
<th>B-B’ RMS &lt;10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Slip (S)</td>
<td>2168 ± 136 m</td>
<td>1148 ± 525 m</td>
</tr>
<tr>
<td>Ramp angle (α)</td>
<td>68° ± 7°</td>
<td>60° ± 9.3°</td>
</tr>
<tr>
<td>Trishear angle (φ)</td>
<td>95° ± 8°</td>
<td>64° ± 21°</td>
</tr>
<tr>
<td>Propagation to slip ratio (P/S)</td>
<td>1.6 ± 0.3</td>
<td>1.5 ± 0.3</td>
</tr>
<tr>
<td>Initial fault tip position (x)</td>
<td>-2132 ± 500 m</td>
<td>5048 ± 654 m</td>
</tr>
<tr>
<td>Initial fault tip position (y)*</td>
<td>-3589 ± 423 m</td>
<td>-1150 ± 390 m</td>
</tr>
<tr>
<td>Final fault tip position (x)#</td>
<td>-771 ± 171 m</td>
<td>— —</td>
</tr>
<tr>
<td>Final fault tip position (y)*</td>
<td>-256 ± 204 m</td>
<td>— —</td>
</tr>
</tbody>
</table>

* meters below sea level
# 0 m at coastline
Table 5-2  Average slip rates, uplift rates, and shortening rates for the Futaba fault based on model-constrained ramp angle and total slip, and dated horizons bracketing the transition from pre-growth to growth strata in the hanging wall anticline.

<table>
<thead>
<tr>
<th></th>
<th>Initiation of Fault Slip (Ma)</th>
<th>Dip Slip Rate (mm/yr)</th>
<th>Uplift Rate (mm/yr)</th>
<th>Shortening Rate (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Age(a)</td>
<td>5.6 ± 0.5</td>
<td>0.39 ± 0.05</td>
<td>0.36 ± 0.05</td>
<td>0.15 ± 0.02</td>
</tr>
<tr>
<td>Minimum Age(b)</td>
<td>3.95 ± 0.2</td>
<td>0.55 ± 0.05</td>
<td>0.51 ± 0.05</td>
<td>0.20 ± 0.02</td>
</tr>
<tr>
<td>Published values</td>
<td>-------</td>
<td>0.05 – 0.1(^c)</td>
<td>0.5 – 0.6(^d)</td>
<td>-------</td>
</tr>
</tbody>
</table>

\(^a\) Oishi Yoshida, 1998; Suto et al, 2005  \(^b\) Nagahashi et al, 2004  \(^c\) Fukushimaken, 1999  \(^d\) Suzuki, 1989
6 Discussion

6.1 Geometry and Kinematics of the Futaba Fault

New structural field data and forward kinematic modeling of the fault related fold associated with the Futaba fault argue for Plio-Quiteranry slip along a steep (50°-75°) basement-involved, reverse fault. The trishear kinematic model used here can reproduce the observed fold geometry along a transect across the hanging wall anticline at the southern tip of the Futaba fault to within observation error (<5°). The previously proposed algorithm for trishear kinematic modeling of bed dips along a topographic profile (Cardozo 2005), requires known bed dips at unit contacts to be well-correlated to their position in an undeformed section in the hanging wall or footwall. The modeling methodology implemented in this study presents an alternative statistical approach that requires only total stratigraphic thickness and well-located bedding dips along a topographic profile.

The model-constrained range of fault ramp angles of 50°-75° W are consistent with fault orientation inferred in the field from shear planes and minor faults. While folds simulated for ramp angles greater than 75°-80° W can reproduce observed bedding data for the hanging wall anticline, they cannot produce beds overturned by 20°-30°, as are observed north of the transect (Figure 3-1A). These results suggest that published values for the sub-surface fault ramp-angle of 80°W-90° from trenching studies are overestimates. This discrepancy may reflect a change in ramp angle due differences in the mechanical properties of the rocks as the fault tip propagates from rigid basement into unconsolidated sediments of the alluvial cover.

Most likely models of the Futaba fault suggest that a minimum of 2 km of dip slip is required to produce the observed fault-related folds. The magnitude of slip required to reproduce folds associated with the Futaba fault suggests that the dominance of strike slip inferred for the Haramachi segment of the Futaba fault (Fukushimaken 1999) is not characteristic of the entire Futaba fault. This magnitude of slip is much greater than the maximum 200m of displacement.
cited in initial characterization of the fault (Mitsui, 1971) and the <50 m of stratigraphic separation along minor faults that offset the Miocene section along the southern portion of the Futaba (Kubo et al., 2003). This can be accounted for, however, in the trishear model because displacement of a bed only occurs after the fault tip has propagated past it. Prior to this point, slip is accommodated by folding of the cover sequence and thinning of the forelimb with no offset. For faults with slow fault propagation rates, bed offset decreases toward the fault tip, and stratigraphic separation at the surface may reflect only a portion of total fault slip.

The differences in fold geometry between the modeled transects of the hanging wall anticline at section A-A’ and the footwall syncline at section B-b’ (Figures 3-1 & 5-5) are interpreted to reflect differences in fault propagation rates related to along strike variability in sedimentary cover thickness. The transition from a broad fold in the hanging wall to a discrete fault that offsets Miocene and Pliocene units coincides with a northward thinning of the cover sequence. At the southern tip of the Futaba fault, the cover sequence is upwards of 2.5 km thick, and slip along the fault is accommodated by folding of the cover sequence (a slow fault propagation rate) rather than by slip along a discrete fault. To the north however, the sedimentary cover sequence thins, and the fault tip likely propagates rapidly toward the surface. This results in little folding in the hanging wall and causes the fault tip to propagate through and cut off the steep forelimb of the fold.

6.2 Tectonic Interpretations

The Plio-Quaternary uplift of the Abukuma Massif is here interpreted to be the result of inversion of a Miocene extensional half-graben by thrust reactivation of a pre-existing normal fault on the eastern flank of the massif. Reactivation of a pre-existing normal fault may account for the fact that there is reverse slip along a fault that is steeper than the predicted ~30° fault ramp
angle for a sub-horizontal maximum compressive stress orientation, $\sigma_1$ (Mitsui 1971, Sato 1994). Neogene inversion of Miocene extensional structures has been similarly argued for several other forearc thrust faults in northeastern Honshu (Kato et al. 2006, Sato 2002). Seismic interpretations of a system of contractional structures near Sendai infer the northernmost Watari segment of the Futaba fault to be part of a system of inverted Miocene extensional faults, and the Watari segment has been interpreted as a footwall shortcut that links at depth with a reactivated Miocene basin-bounding fault (Sato, 2008 personal communication). The southward projection of this fault is aligned with the Haramachi and Namie segments of the Futaba fault.

Average dip slip rates for the Futaba fault determined from kinematic modeling are five to ten times greater than those reported from trenching of the Haramachi segment ~70 km north of section A-A’. Slip rates determined from trenching at this site show that strike slip displacement accumulated over two events is nearly twice that of dip displacement, resulting in the classification of the active Futaba fault as a strike slip fault. The northern portion of the Haramachi segment however, overlaps with the Watari segment, (Figure 2-1) which steps to the east ~4 km from the mountain front. This step-over may represent a reactivated transfer zone in the Miocene extensional system where slip along the modern Futaba fault system is transferred from the Haramachi segment to the Watari segment.

The differences in the magnitude and direction of slip between model results and trenching-determined slip rates may reflect a difference between long term slip sense and displacement on the most recent event or along-strike variation in slip sense. The former would imply that Holocene slip may not be reflective of long-term slip on the Futaba fault. The latter would imply a decrease in the magnitude of dip slip and an increase in the obliquity of the slip vector from the southern tip of the Namie segment north toward the Haramachi segment. Such a variation in slip sense may be related to a transfer of slip from the Haramachi segment to the Watari segment of the Futaba fault. Similar changes in slip sense have been observed along other
overlapping faults due to local changes in the orientation of the stress field within transfer zones (Acocella et al. 1999). Similar spatial variation in the magnitude and obliquity of slip have been reported in for an analogous forearc thrust fault located west of the Kitakami massif in a preliminary finite fault model for the 2008 Iwate earthquake (Hikima 2008) and in patterns of surface ruptures.

The Futaba fault represents one fault in a system of contractional structures and contributes 0.1-0.2 mm/yr of inner forearc shortening since the Pliocene to the total shortening budget across the forearc of northeastern Japan. Numerous mapped thrust faults north and west of the Abukuma massif are actively shortening the forearc (Figure 2-1). In addition, uplifted marine terraces east of the Abukuma massif (Suzuki 1989) argue for the existence of at least one additional thrust fault offshore of the Abukuma massif. Collectively, this system of faults produces a net shortening across the backarc, arc and forearc of Northeastern Japan.

The accumulation of permanent strain inboard of the plate boundary suggests that the entire forearc may be responding to changes in plate boundary tractions related to Neogene subduction erosion and acts as a deformable rather than a rigid backstop. Shortening accommodated by the Futaba fault and other forearc structures may result in the loading of the outer forearc, the delivery of a pulse of sediments generated from uplift and erosion in the inner forearc, and the generation of a sub-aqueous sedimentary basin. Additionally, inner forearc shortening may result in an increase in forearc slope angle and an accompanied increase in rates of sediment transport from the inner forearc to the outer forearc.

Therefore, a portion of the sediment record interpreted as the result of subsidence of the outer forearc resulting from basal erosion of the upper plate may instead reflect processes associated with inner forearc shortening. The potential of inner forearc shortening to influence outer forearc subsidence is of particular significance considering that outer forearc subsidence patterns along Northeastern Japan and other erosive margins have been interpreted to result only
from basal tectonic erosion of upper plate material. This calls into question the relative contribution of inner forearc shortening to calculated rates of subduction erosion and implies that forearc shortening plays an important role in the mass balance of erosive margins.
7 Conclusions

New structural field data and forward trishear kinematic modeling of the fault related folds associated with the Futaba fault collectively argue for the initiation of slip along a steep, basement-involved, reverse fault during the latest Miocene to Early Pliocene. Monte Carlo simulations of fault-related fold geometry – constrained by bedding dips along a topographic profile – result in most likely ramp angles of 50º-75º and most likely total dip displacement of 1900-2600m. Dated tephra horizons that bracket the growth – pre-growth transition at the southern tip of the Futaba fault constrain the onset of deformation to 5.6 to 3.95 Ma. Combining the timing of fault initiation with best-estimates of fault ramp angle and total slip yields slip rates of 0.4-0.6 mm/yr, uplift rates of 0.4-0.5 mm/yr and shortening rates of 0.1-0.2 mm/yr for the Futaba fault.

Reverse slip along the Futaba fault is interpreted to result from thrust reactivation of a Miocene extensional fault associated with the opening of the Sea of Japan. The Futaba fault is one of a system of forearc contractional structures that are actively shortening the forearc of northeastern Japan; the Futaba fault alone has contributed ~800m of forearc shortening since the Pliocene. The contemporaneous occurrence of inner forearc shortening and outer forearc subsidence along the northeastern Japan margin suggests that the two processes may be genetically linked, that the entire forearc may be responding to changes in plate boundary tractions related to Neogene subduction erosion, and that inner forearc shortening may influence offshore subsidence records classically interpreted to reflect basal tectonic erosion.
References


Sato, H. 2002. Tectonic evolution and deep to shallow geometry of Nagamachi-Rifu active fault system, NE Japan. *Earth, planets, and space* 54(11), 1039-1043.


Suzuki, T. 1989. Late Quaternary crustal movements deduced from marine terraces and active faults, Japan Coastal region, Northeast Japan. *Geographical Reports of Tokyo Metropolitan University* 24(31-42).


Appendix: MATLAB codes

Function Monte_Trishear_Inputs.m

This script initializes a Monte Carlo simulation that will run # iterations of the trishear algorithm in the script trishear_IO.m. The script defines the timesteps and total model run time for each iteration of trishear_IO.m, a model slip rate, and options for the sedimentation a growth strata plotting rates and an erosion surface. The Monte Carlo simulation randomly assigns values for fault ramp angle (ramp), trishear angle (phi), and propagation to slip ratio (PS) bound by user-defined minimum and maximum values. The script calculates an initial fault tip position based on a range of modern, surface fault tip positions in the x-coordinate direction (tipXsurf) and a range of depths for the initial fault tip (tipY) for the assigned ramp angle.

This script calls the function trishear_IO.m.

INPUTS:
- tinitial - minimum model run time
- tfinal - maximum model run time
- tstep - time steps between tinitial and tfinal at which and RMS fit between the model and the data will be calculated.
- nruns - number of iterations of the Monte Carlo simulation
- vo - slip rate
- ramp - fault ramp angle, degrees
- phi - trishear angle, degrees
- PS - propagation to slip ratio
- tipXsurf - range of x-coordinate positions for the surface projection of the modern fault tip in map view (meters from the end of the section)
- tipY - range of depths of initial fault tip (m)

OUTPUTS:
- (saved to .mat files with the following names appended with timestamp)
- parameters - cell matrix containing all model outputs for every run, where column 1 = runnumber, col2 = time, col3 = phi, col4 = vo,
- col5 = ramp angle, col6 = PS, col7 = initial fault tip position,
- x-coordinate, col8 = initial fault tip position y-coordinate, col9 = RMS (output from script calc_RMS.m), col10 = a matrix containing all residuals (output from script calc_RMS.m), col11 = interpolated model dips at the x-y positions of observed bed dips
- input_parameter_space - saves all model inputs in the script

clear all; close all;
% Load bed_Data .mat file
load init_bed_data
% Load dip profile .mat data file
load('stop37_dip_profile_andgrowth_data3.mat')
dt = 1e4; % do not change

% Time %
  tinitial = 2.0e6;
  tfinal = 2.5e6;
  tstep = .05e6;

% Determine times to stop model and do RMS calc %
  tpause = [tinitial:tstep:tfinal];
  n=tfinal/dt;

% Erosion surface
  erosion = 50000; % y-value of erosion surface

% Sedimentation rate for growth strata
  s = 2e-4; % m/yr
  st=2; % frequency at which growth beds will be plotted

% Create beds matrices %
  bedsx = [bedsxinit; zeros(n/st, size(bedsxinit,2))*NaN];
  bedsy = [bedsyinit; zeros(n/st, size(bedsyinit,2))*NaN];

% Define Constant Parameters%
  vo = 1e-3;
  vo = repmat(vo, 1, n);

% Output labels
  labels = {'runnumber' 'tfinal' 'phi' 'vo' 'PS' 'rampangle' ...
            'tipinitX', 'tipinitY', 'RMS', 'R', 'dips_interp'};

%-------------------------------%
% Time and date stamp %
  day = date;
  month = day(4:6);
  c = clock; % year month day hour minute seconds %
  day = num2str(c(3)); year = num2str(c(1));
  hour = num2str(c(4)); minutes = num2str(c(5));
  date_time = [month, num2str(c(3)), '_', num2str(c(1)), ...
               '_', num2str(c(4)), '_', num2str(c(5))];
  name = ['parameters_' date_time];
%-------------------------------%

% Monte Carlo Loop %
  runnumber = 1;
  for nruns=1:2;
    rm = rand(1,5);

    % Chose random values for ramp, phi, PS, tipXsurf and tipY %
rampmin = 30;
rampmax = 90;
ramp = pi/180*(round(rampmin+rm(1)*(rampmax-rampmin)));
%uniform prior
ramp = repmat(ramp, 1, n);

phimin = 40;
phimax = 130;
phi = pi/180*round(phimin+rm(2)*(phimax-phimin));
phi = repmat(phi, 1, n)/2;

PSmin = 0.5;
PSmax = 3.5;
PS = PSmin+rm(3)*(PSmax-PSmin);
PS = repmat(PS,1,n);
tipYmin = -1400;
tipYmax = 0;
ttY = round(tipYmin+rm(4)*(tipYmax-tipYmin));

% Current fault tip position in map view %
tipXsurfmin = 5000;
tipXsurfmax = 7200;
ttXs = round(tipXsurfmin+rm(2)*(tipXsurfmax-tipXsurfmin));

% Calculate tipX at depth based on tipXsurf, tipY, and ramp %
ttX = round((ttY-3000)/tan(ramp(1)) + ttXs);
tipinit = [ttX ttY];
%temp(nruns,:) = [180/pi*ramp(1) 180/pi*phi(1)*2  PS(1)  ttXs ttY ttX];

[runnumber, parameters_temp, field] = trishear_IO(tipinit, dx, dt, tfinal, n, phi, vo, PS, ramp, st, L, bedsx, bedsy, bedsxinit, bedsyinit, erosion, s, ncols_pregrowth, nrows_pregrowth, tpause, runnumber, dipposx, dipposy, date_time, dip_profile);

if runnumber==length(tpause)+1
    parameters = [labels; (parameters_temp)];
else
    parameters = [parameters; (parameters_temp)];
end
if mod(nruns, 2)==0
    nruns
    save(name, 'labels', 'parameters')
end
end

%-------------------------

save(name, 'labels', 'parameters')
name = ['input_parameter_space' date_time];
save(name, 'L', 'bedsxinit', 'bedsyinit', 'dx', 'ncols_pregrowth', ...
    'nrows_pregrowth', 'dip_profile', 'dt', 'tfinal', 'tpause', ...
    'erosion', 's', 'st', 'phimin', 'phimax', ...
    'vo', 'PSmin', 'PSmax', 'ramp', 'tipXsurfmin', 'tipYmin', ...
    'tipXsurfmax', 'tipYmax', 'field');
%-------------------------

58
Function trishear_IO.m

function [runnumber, parameters_temp, field] = trishear_IO(tipinit, dx, dt, tfinal, n, phi, vo, PS, ramp, st, L, bedsx, bedsy, bedsxinit, bedsyinit, erosion, s, ncols_pregrowth, nrows_pregrowth, tpause, runnumber, dipposx, dipposy, date_time, dip_profile)

% The following script simulates deformation of a basement-involved reverse fault 
% using the trishear kinematic model (Erslev, 1991) using the velocity field solutions 
% presented in Zhender and Allmendinger (2000). The script requires initial bed 
% geometry, observed dip data, and Trishear Inputs to be designated by the m-file 
% Monte_Trishear_Inputs.m. Monte_Trishear_Inputs.m will designate values for 
% tipinit, dx, dt, tfinal, n, phi, vo, PS, ramp, st, L, bedsx, bedsy, bedsxinit, bedsyinit, 
% erosion, s, ncols_pregrowth, nrows_pregrowth, tpause, runnumber, dipposx, 
% dipposy, date_time, and dip_profile. This script allows for the additions of 
% growth strata at a continuous depositional rate onto a growing structure and can 
% have an arbitrary erosion surface above which material will be removed from 
% the system.

% The script will plot the simulation of fold growth overlain on the observed bed dip 
% profile. This option can be turned off to increase processing speed.

% INPUTS
% *All inputs are designated in the script Monte_Trishear_Inputs.m

% OUTPUTS
% runnumber - the number of the model realization, each unique set 
% of tfinal, ramp, phi, PS, and tip position are one model run 
% parameters_temp - temporary matrix of model input values, RMS, 
% residuals and interpolated slopes. These values are 
% concatenated in the script Monte_Trishear_Inputs.m into a 
% single file, parameters.
% field - 's' if using the sine velocity field, 'll' if linear field

% close all 
veloc_field = 's';  %'s' for sine field, 'll' for linear field with s=1
scale = 0.5;  %scale factor for quiver plots

% Calculate Initial Fault Ramp %
% Project back from tipinit 
FX = tipinit(1) - 10*dx:dx:tipinit(1); 
FY = tan(ramp(1))*FX - tan(ramp(1))*tipinit(1) + tipinit(2);

% SET UP MODEL SPACE FOR VELOCITY FIELD DISPLAY %
X= linspace(dx, max(max(bedsx)) - tipinit(1)+dx, 30); 
Y= linspace(-max(max(bedsx))/2, max(max(bedsx))/2, 30);
\[(x, y) = \text{meshgrid}(X, Y);\]

% Make empty matrices
Vx = zeros(size(x)); Vy = zeros(size(y));
tz = zeros(size(bedsx));
Vbx = zeros(size(bedsx)); Vby = zeros(size(bedsy));
B = zeros(size(bedsx));
transbedsx = 0; transbedsy = 0;
transfzx = 0; transfzy = 0;

%%
% translate beds such that fault tip is the origin
bedsx = bedsx - tipinit(1);
bedsy = bedsy - tipinit(2);

% Rotate beds into x,y, trishear velocity field ref frame
bedsxrot = bedsx*cos(-ramp(1)) - bedsy*sin(-ramp(1));
bedsyrot = bedsy*cos(-ramp(1)) + bedsx*sin(-ramp(1));

%%
%--------- RUN TIME LOOP -------
%%
for n = 1:t final/dt
if n>1
  % Rotate beds into x,y, trishear velocity field ref frame
  bedsxrot1 = bedsxrot*cos(-ramp(n)-ramp(n-1)) - bedsyrot*…
             sin(-(ramp(n)-ramp(n-1)));
  bedsyrot1 = bedsyrot*cos(-(ramp(n)-ramp(n-1)))+ bedsxrot*…
             sin(-(ramp(n)-ramp(n-1)));
  bedsxrot=bedsxrot1;
  bedsyrot=bedsyrot1;

  % move back 1 slip unit from n-1 step in x and y if n>1 (when n==1, transfz=0)
  bedsxrot = bedsxrot - vo(n)*PS(n)*dt;
end

% Trishear boundary slopes in x,y, trishear space
mbcu = tan(phi(n));
mbcl = tan(-phi(n));

% Calculate points in trishear zone (tz) and hanging wall (hw)
tz = double (bedsyrot < bedsxrot .* tan(phi(n)) & bedsxrot > bedsxrot .* …
     tan(-phi(n)));
hw = double (bedsyrot > 0 & bedsyrot >= bedsxrot .* tan(phi(n)));
fw = double (bedsyrot < 0 & bedsxrot <= bedsxrot .* tan(-phi(n)));

% Calculate tz and hw for velocity display field
if n>1
  % calculate points lower than current fault tip in hanging wall that should
% remain in foot wall if ramp angle changes with time
fw = double(bedsyrot < 0 & bedsyrot <= bedsxrot .* tan(-phi(n))) +
    PS(n)*vo(n)*dt*tan(ramp(n));
fw_new = double(hwn_1 == 0 & tz==0 & bedsxrot <= 0 & bedsy <= …
            tipinit(2) + transtzy);
fw2_new = double(hw2n_1 == 0 & tz2==0 & x <= 0);
end

% *--------------------------------------------------------------------
% if veloc_field == 's'
% field = 'Sine';
% % Trishear Sine Velocity Field Pregrowth%
B(tz==1) = bedsyrot(tz==1).*pi./(2.*bedsxrot(tz==1).*tan(phi(n)));
Vbx(tz==1) = vo(n).*0.5.*sin(B(tz==1))+B(tz==1).*sin(B(tz==1))-pi./2));
Vby(tz==1) = vo(n).*tan(phi(n)).*(cos(B(tz==1))+B(tz==1).*sin(B(tz==1))-pi./2));
% Solve for velocity field display
B2 = y.*pi./(2.*x.*tan(phi(n)));
Vx(tz2==1) = vo(n).*0.5.*(sin(B2(tz2==1))+1));
Vy(tz2==1) = vo(n).*tan(phi(n)).*(cos(B2(tz2==1))+B(tz==1).*sin(B(tz==1))-pi./2));
elseif veloc_field == 'l1'
field = 'linear1';
% Trishear Linear Velocity field Pregrowth
S=1;
Vbx(tz==1) = vo(n)./2.*(sign(bedsyrot(tz==1)).*(abs(bedsyrot(tz==1)).*(tan(phi(n))).*bedsxrot(tz==1)).^((1+S)/S);)
Vby(tz==1) = vo(n)/2.*tan(phi(n))./(1+S).*((abs(bedsyrot(tz==1)).*(tan(phi(n))).*bedsxrot(tz==1)).^((1+S)/S));
end

% Calculate velocity field in HW and FW
Vbx(hw==1) = vo(n);
Vby(fw==1) = 0;
Vbx(fw==1) = 0;
Vx(hw2==1) = vo(n);
Vbx(hw2==1) = vo(n);
% % Numerical integration %
% % Solve for position at n within trishear zone %
bedsxrot(tz==1) = bedsxrot(tz==1) + Vbx(tz==1).*dt;
bedsyrot(tz==1) = bedsyrot(tz==1) + Vby(tz==1).*dt;
% % Solve for position at n+1 within trishear zone %
bedsxrot(hw==1) = bedsxrot(hw==1) + vo(n).*dt;
% %-------------------------------------------------------------------%

%% Rotation and translation into N,Z, earth-centered reference frame
% xy position translation along propagating fault tip
transtzx = PS(n)*vo(n)*dt*cos(ramp(n)) + transtzx;
transtzy = PS(n)*vo(n)*dt*sin(ramp(n)) + transtzy;

% Rotate position matrix for Vx and Vy and translate to tipinit %
bedsx = bedsxrot*cos(ramp(n)) - bedsyrot*sin(ramp(n)) + tipinit(1);
bedsy = bedsyrot*cos(ramp(n)) + bedsxrot*sin(ramp(n)) + tipinit(2);

% Translate beds along fault %
if n>1
  transbedsx = PS(n)*vo(n)*dt*cos(ramp(n)) + transbedsx;
  transbedsy = PS(n)*vo(n)*dt*sin(ramp(n)) + transbedsy;
  bedsx = bedsx + transbedsx;
  bedsy = bedsy + transbedsy;
end

% For Display:
% Create x,y points to define trishear zone boundaries
bcx = 0:max(max(bedsxrot));
bcuy = mbcu .* bcx;
bcly = mbcl .* bcx;

% Rotate and translate velocity field for display %
Vxrot = Vx*cos(ramp(n)) - Vy*sin(ramp(n));
Vyrot = Vy*cos(ramp(n)) + Vx*sin(ramp(n));

xrot = x*cos(ramp(n)) - y*sin(ramp(n)) + tipinit(1);
yrot = y*cos(ramp(n)) + x*sin(ramp(n)) + tipinit(2);

% Translate velocity field along fault one PS increment
xrot = xrot + transtzx;
yrot = yrot + transtzy;

% Rotate trishear zone boundaries and translate to tipinit %
Zbcux = bcx*cos(ramp(n)) - bcuy*sin(ramp(n)) + tipinit(1);
Nbcuy = bcuy*cos(ramp(n)) + bcx*sin(ramp(n)) + tipinit(2);

Zbclx = bcx*cos(ramp(n)) - bcly*sin(ramp(n)) + tipinit(1);
Nbcly = bcly*cos(ramp(n)) + bcx*sin(ramp(n)) + tipinit(2);

% Translate trishear zone boundaries along fault %
Zbcux = transtzx + Zbcux;
Zbclx = transtzx + Zbclx;
Nbcuy = transtzy + Nbcuy;
Nbcly = transtzy + Nbcly;

% Calculate new fault L %
FXnew = FX(end) + PS(n)*vo(n)*dt*cos(ramp(n));
FYnew = FY(end) + PS(n)*vo(n)*dt*sin(ramp(n));
FX = [FX, FXnew];
FY = [FY, FYnew];
% Adjust fw, hw for variable fault angles
    hwn_1 = hw;
    hw2n_1 = hw2;

%% ADD GROWTH STRATA

{%
  if mod(n,st)==0
    % Identify highest row number with bed data value (not NaNs)
    topbedI = find(isnan(bedsy(:,end))==0,1, 'last');
    temp = max(bedsx((bedsy>= s*dt*st + bedsy(nrows_pregrowth-1+(n/st), end))));
    % x value where growth and pregrowth intersect
    gx = linspace(min(min(bedsx(nrows_pregrowth,:))), L, L/dx+1);
    gy = repmat(s*dt*st + bedsy(topbedI, end), 1, L/dx+1);
    if isempty(temp) == 0
        gx(gx <= temp) = NaN;
        gy(gx<=temp) = NaN;
    end
    gx=gx-tipinit(1) - transbedsx;
    gy=gy-tipinit(2) - transbedsy;
    % Rotate g matrices and add to bedsrot
    gxrot = gx*cos(-ramp(n)) - gy*sin(-ramp(n));
    gyrot = gy*cos(-ramp(n)) + gx*sin(-ramp(n));
    bedsxrot(nrows_pregrowth + n/st, :) = gxrot;
    bedsyrot(nrows_pregrowth + n/st, :) = gyrot;
  end
%
%
%% ADD EROSION

% Erosion level is set such that:
% 1) shoreline is fixed at modern position: ((ceil(dipposx(end,1)/dx))+1))
% 2) initial erosive level is dx above highest pre-deformation bed
% 3) erosive level gains elevation through time (to simulate
% subsidence) at a rate == to sed-rate. Therefore accom space is
% contant through time

% Find indices of points whose x-values are > than shoreline
shoreline = ((ceil(dipposx(end,1)/dx))-2)*dx;
elevel = dipposy(end,1) + dt*n*s/6;
e = double(bedsx>shoreline & bedsy>elevel);

% Remove eroded material
bedsy(e==1) = NaN;
bedsx(e==1) = NaN;
bedsxrot(e==1) = NaN;
bedsyrot(e==1) = NaN;
% Turn plot function off (comment) for fast computation %
if mod(n,20) ==0 | n==tfinal/dt
    clf
    hold on
%quiver(xrot,yrot,Vxrot, Vyrot, scale, 'g')
end

% Plot deformed pregrowth beds%
for i=1:21 %nrows_pregrowth-1 +1
    hold on
    plot (bedsx(i,:), bedsy(i,:), 'r')
end
for i=22:27
    plot(bedsx(i,:), bedsy(i,:), '--b')
end
for i=28:31
    plot(bedsx(i,:), bedsy(i,:), '-y')
end

% Plot growth beds%
for i= nrown_pregrowth+1 : nrown_pregrowth+1 +floor(n/st)
    hold on
    plot (bedsx(i,:), bedsy(i,:), 'k')
end

% Plot Trishear zone boundaries
plot (Zbcux, Nbcuy, '--k'); plot (Zbclx, Nbcly, '--k')
axis([0, L+dx, min(FY),max(max(bedsyinit))+1.5*abs(max(max(bedsyinit))) ... 
     - min(min(bedsyinit)))])
% Plot Fault
hold on; plot (FX, FY, 'k');

% Plot Observed bed dip profile
for i=1:size(dipposx,1)
    hold on
    plot(dipposx(i,:), dipposy(i,:))
end
% Plot point at initial K sed outcrop/granite contact
plot(2316, 216+3000, '.b')
xlabel 'Distance (m)'; ylabel 'Elevation (m)'; drawnow
%%% Calculate RMS fit of data to model %

if max(n*dt == tpause)==1

% RUN STATISTICS SCRIPT

[R, RMS, dips_interp]=calc_RMS(bedsx, bedsy, dip_profile);

% Plot Observed bed dip profile
for i=1:size(dipposx,1)
    hold on
    plot(dipposx(i,:), dipposy(i,:))
end

% Add text with Trishear Parameters, RMS
mx=max(max(bedsx));
my=max(max(bedsyinit));
myi=abs(max(mx(bedsyinit)) - min(min(bedsyinit)));
labels = {{'Total Slip=' num2str(vo(n)*n*dt) 'm'}; {'Ramp=' num2str(round(180/pi*(ramp(n)))) 'deg'}; {'PS=' num2str(PS(n))}; ...
        {'phi=' num2str(round(180/pi*(phi(n)))) 'deg'}; ...
        {'tipinit=[' num2str(tipinit(1)) 'm',', ' num2str(tipinit(2)) 'm']'};};

% Save model outputs
%save(varname, 'bedsx', 'bedsy', 'FX', 'FY', 'Zbcux', 'Zbclx', 'Nbcuy', 'Nbcly', ....
%        'nrows_pregrowth', 'xrot', 'yrot', 'Vxrot', 'Vyrot')
% Save the figure
%sh=gcf;
%saveas(h, varname, 'fig');

figure; plot(dip_profile(1,:), R, 'or')
axis([min(dip_profile(1,:)), max(dip_profile(1,:)), -90, 90])
xlabel 'Distance (m)'; ylabel 'Residual (Predicted-observed)'
title ('Residuals for model');

% Write parameters
parameters_temp(c,:) = [runnumber, n*dt, 2*180/pi*phi(n), vo(n), PS(n), 180/pi*(ramp(n)),tipinit(1), tipinit(2), RMS, {R} {dips_interp}];

end
end
c=c+1;
runnumber=runnumber+1;
end
clear bedsx bedsy
Function calc_RMS.m

function [R RMS dips_interp] = calc_RMS_lMio_only(bedsx, bedsy, dip_profile);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% function [R RMS dips_interp] = calc_RMS_lMio_only(bedsx, bedsy, dip_profile);
% This script will calculate the residuals and RMS fit between bed positions calculated in
% the script trishear_IO and observed bedding data saved in and in the matrix dip_profile.
% Calc_RMS.m is called in function trishear_IO

% INPUTS:
% bedsx - output x bed positions, from trishear23_IO
% bedsy - output y bed positions, from trishear23_IO
% varnmae - genvarname(runnumber, date_Time), made in trishear23_IO
% dip_profile - 3row matrix containing [x;y;dip] for observed bed dips

% OUTPUTS:
% R - vector of residuals (model-observed) for each observed bed dip
% RMS - scalar of RMS for model realization runnumber#
%
%
% Calculates the dips for each x,y point on each bed, as the slope of a line
% between point i+1 and point i-1. (points i and end have no slope value)
nans = zeros(size(bedsx,1),1)*NaN;
dips = [nans,(bedsy(:,3:end)-bedsy(:,1:end-2))./(bedsx(:,3:end)-bedsx(:,1:end-2)),nans];
dips = 180/pi*(atan(dips));

dipsb = dips(22:27,:);
dipsbzeros = isnan(dipsb);
dipsb(dipsbzeros==0)=1;
dips=[dips(1:21,:);dipsb;dips(28:end,:)];

% Remove data points with NaN dips:
% griddata interpolation cannot run if there are NaN values
dips1=dips; bedsx1=bedsx; bedsy1=bedsy;
%dips1(isnan(dips)==1)=[];
dips1(isnan(dips)===1 | isnan(bedsx)==1 | isnan(bedsy)==1)=[];
%bedsx1(isnan(dips)==1) = [];
%bedsy1(isnan(dips)==1 | isnan(bedsx)==1 | isnan(bedsy)==1)=[];
%bedsy1(isnan(dips)==1 | isnan(bedsx)==1 | isnan(bedsy)==1)=[];

% Plot dips

%}
figure
   for i=1:size(bedsx,1)
      hold on
      scatter(bedsx(i,:), bedsy(i,:), 5, dips(i,:))
   end
   colorbar; xlabel 'Distance (m)'; ylabel 'Elevation (m)'
   title ('Slope field for model ', varname)
%

%%% Interpolate slopes
% interpolate output trishear slopes to x,y points of observed dip profile
dips_interp = griddata(bedsx1, bedsy1, dips1, dip_profile(1,:), dip_profile(2,:));
%
% Residuals
% R = model - observed
R = dips_interp - (dip_profile(3,:));
%\n%%% Plot Residuals %%%%%%%%
figure; plot(dip_profile(1,:), R, 'or')
axis([min(dip_profile(1,:)), max(dip_profile(1,:)), -180, 180])
xlabel 'Distance (m)'; ylabel 'Residual (Predicted-observed)'
title ('Residuals for model ', varname)
hold on; a=[min(dip_profile(1,:)),max(dip_profile(1,:))]; b=[0,0];
plot(a,b); h=gcf;
saveas(h,[varname, '_residuals', 'fig'])
%
%%% Calculate RMS %%%%%%%%
numR = length(R) - length(find(isnan(R)));
RMS = sqrt((nansum(R(1:end).^2))/numR);